EPICA | Electronic-Photonic Integrated Circuits for Aerospace

Tutorial #3
Inverse Design of a Power Splitter for Silicon Photonics

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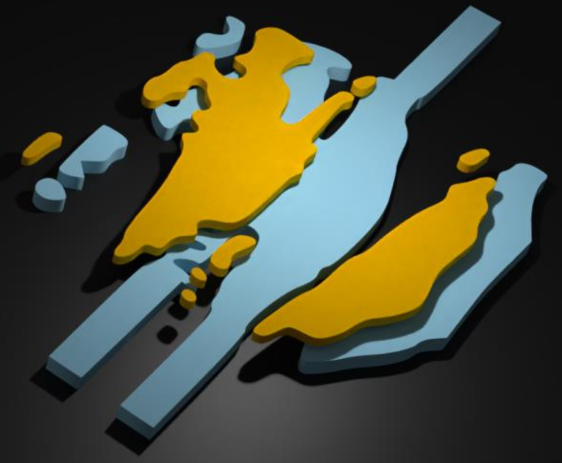

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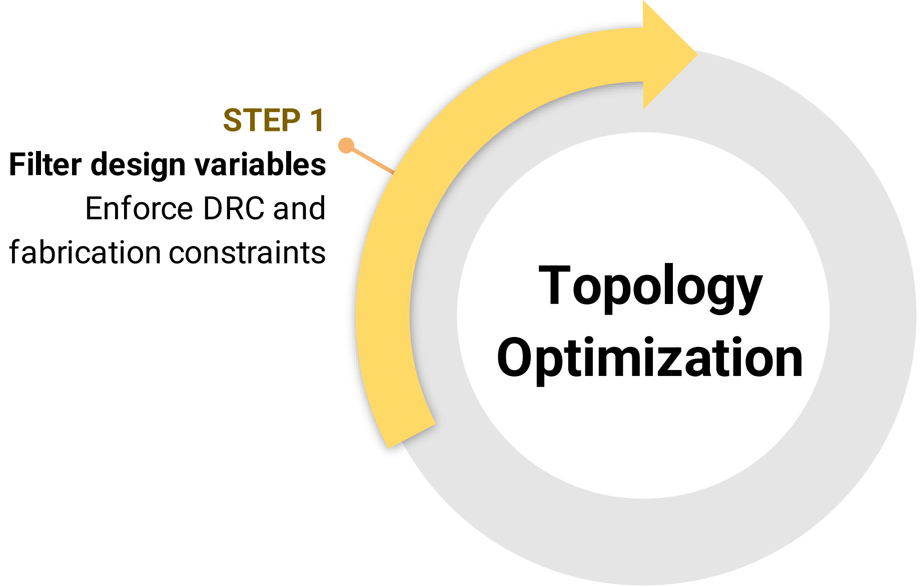
Tutorial Overview and Objectives

Today's primary goal: design a silicon-photonics power splitter

- Discuss **adjoint optimization** (in comparison to other techniques)
- Understand how gradients are computed using Meep's **hybrid-domain adjoint solver**
- Understand the **density-based** topology optimization design flow
- Discuss the importance of **objective function formulations**
- Discuss fabrication constraints

Density-Based Topology Optimization



Density-Based Topology Optimization

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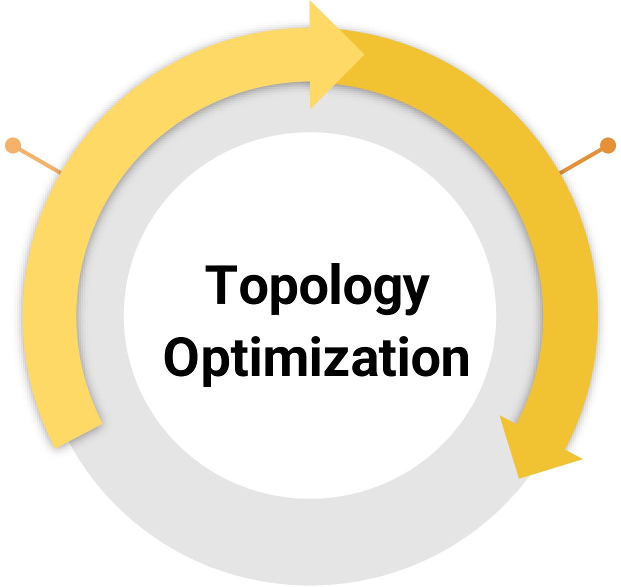
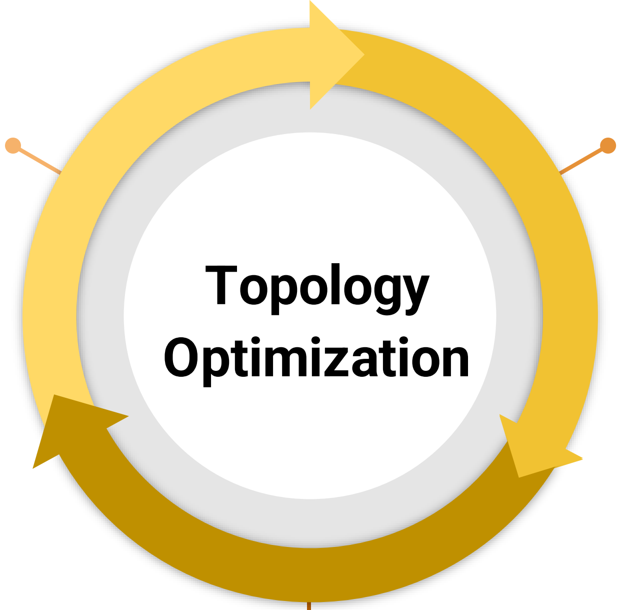
STEP 1
Filter design variables
Enforce DRC and fabrication constraints



STEP 2
Forward simulation (forward propagation)
Measure performance of device and prepare gradient calculation

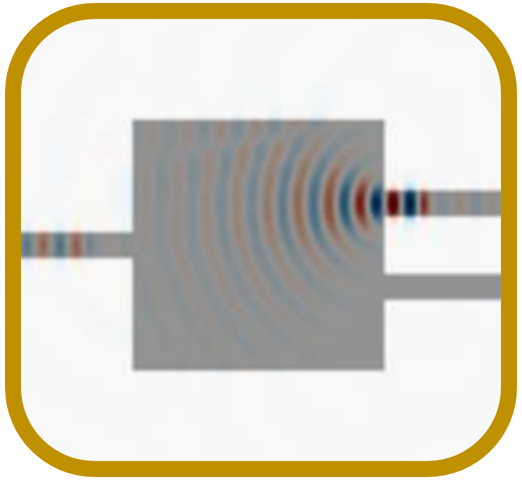
Density-Based Topology Optimization

STEP 1
Filter design variables
Enforce DRC and fabrication constraints



STEP 2
Forward simulation (forward propagation)
Measure performance of device and prepare gradient calculation

STEP 3
Adjoint simulation (backpropagation)
Calculate the gradient of merit function w.r.t. every design parameter simultaneously (~10^5 parameters)



Sigmund, O., & Maute, K. (2013). Topology optimization approaches. *Structural and Multidisciplinary Optimization*, *48*(6), 1031-1055.

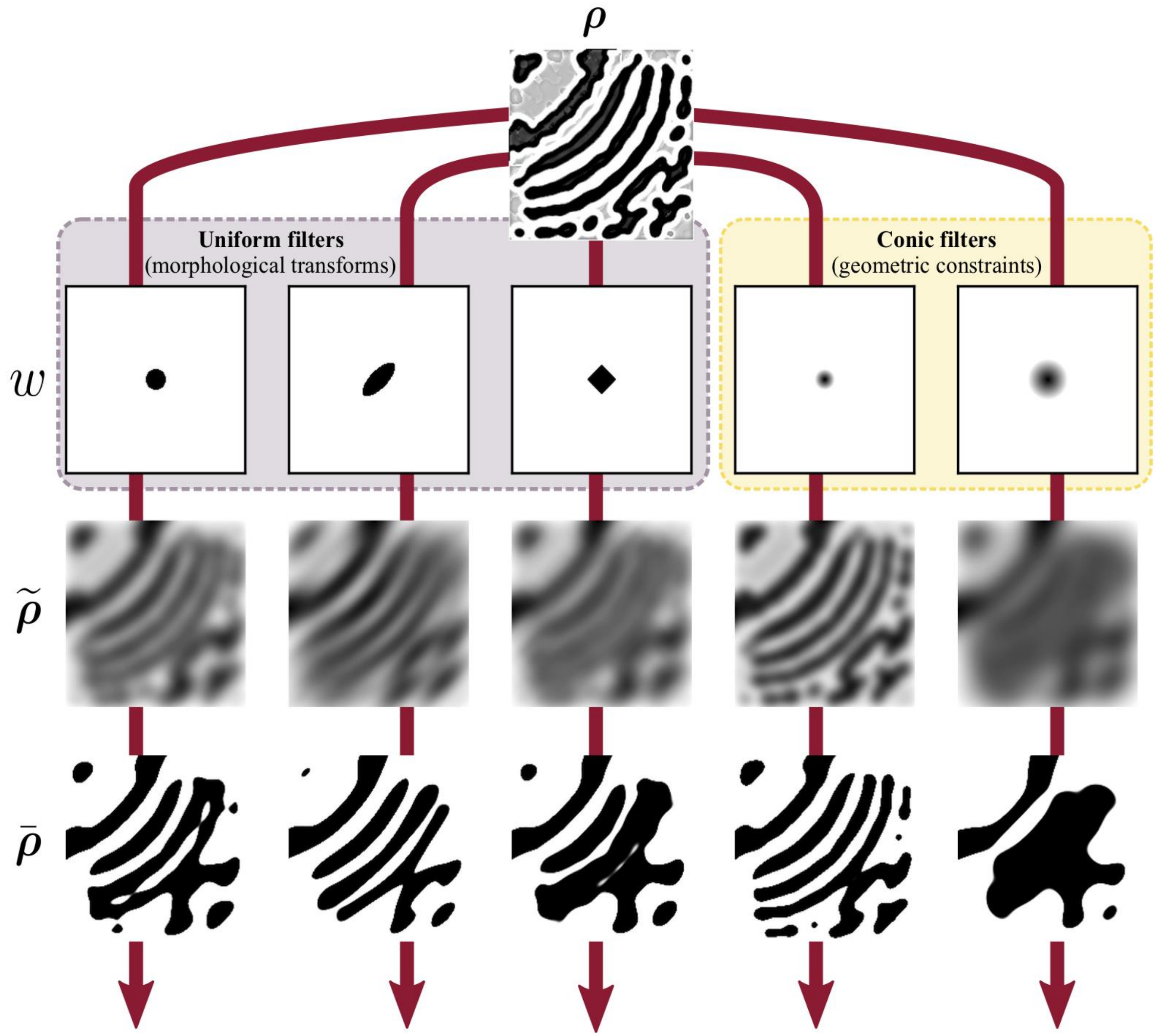
Density-Based Filters and Projection Functions

Original design parameters

Filter kernel

Filtered field

Projected field

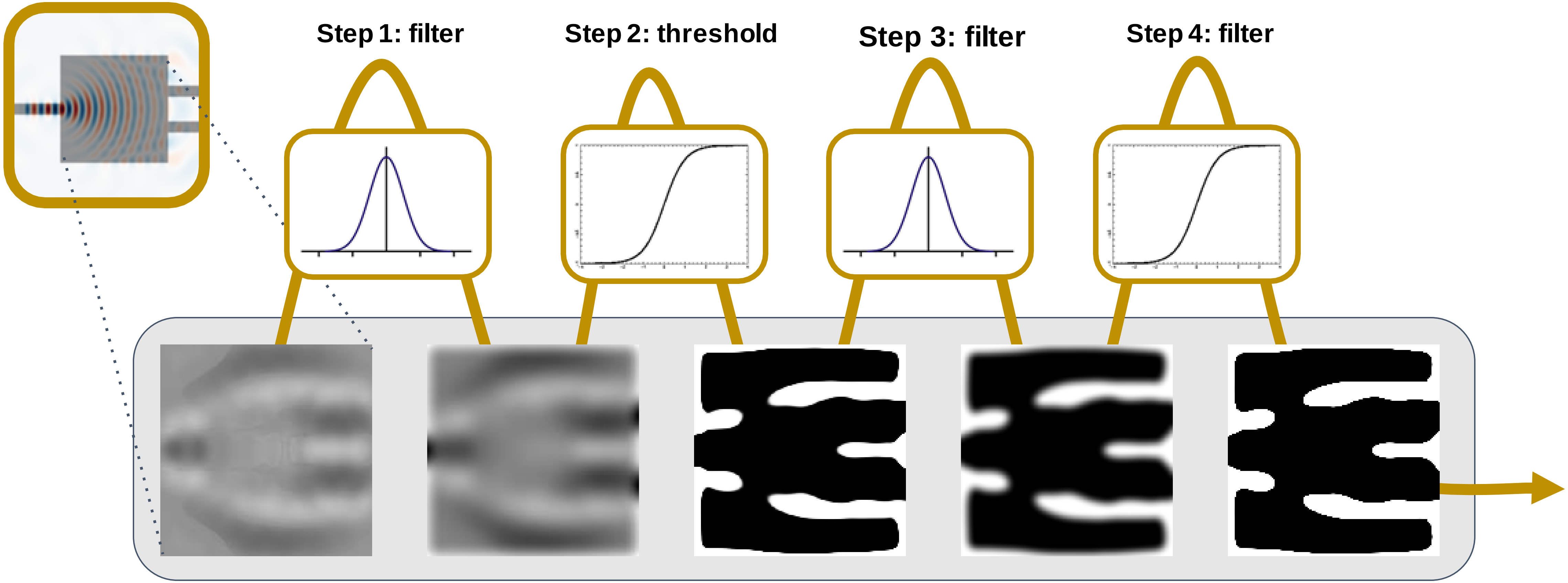


Key point: image processing routines enable efficient control of design parameters

Also, *easy to differentiate!*

Hammond, A. M., et al., "Photonic topology optimization with semiconductor-foundry design-rule constraints", Optics Express 2021.

Flexible Filter Flow



- Cascaded linear and nonlinear elements -- looks just like convolutional ANN!
- Different filter/projection steps can enforce different DRC fabrication constraints
- Very heuristic and preliminary -- lots of research opportunities (especially with the fab)

Christiansen, R. E., Lazarov, B. S., Jensen, J. S., & Sigmund, O. (2015). Creating geometrically robust designs for highly sensitive problems using topology optimization. *Structural and Multidisciplinary Optimization*, *52*(4), 737-754.

Objective Function Formulation

Naive MSE maximization approach

```
def J(source,arm_top,arm_bottom):
    power = npa.abs(arm_top/source)**2 + npa.abs(arm_bottom/source)**2
    return npa.mean(power)
```

Log of MSE error (expand dynamic range)

```
def J(source,arm_top,arm_bottom):
    power = npa.abs(0.5-npa.abs(arm_top/source)**2) + npa.abs(0.5-npa.abs(arm_bottom/source)**2)
    return 10*npa.log10(npa.abs(npa.mean(err)))
```

Minimax approach (via epigraph formulation)

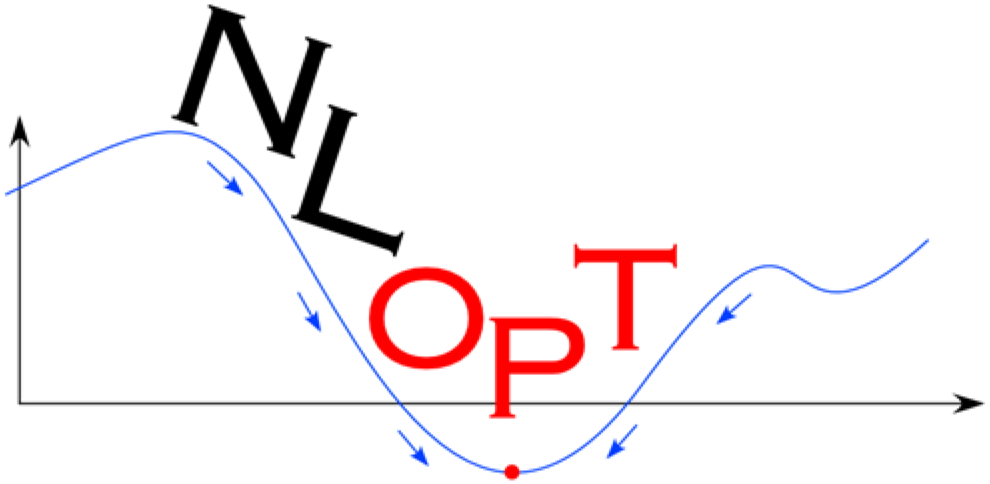
```
def J(source,arm_top,arm_bottom):
    err = npa.abs(0.5-npa.abs(arm_top/source)**2) + npa.abs(0.5-npa.abs(arm_bottom/source)**2)
    return 10*npa.log10(npa.abs(err))
```

Multiobjective, minimax approach (via epigraph formulation)

```
def J_top(source,arm_top,arm_bottom):
    return npa.log10(npa.abs(0.5-npa.abs(arm_top/source)**2))
def J_bottom(source,arm_top,arm_bottom):
    return npa.log10(npa.abs(0.5-npa.abs(arm_bottom/source)**2))
```

Optimization Methods

- Optimization challenges
  - Several variables (10^5-10^6)!
  - Requires many different inequality/equality constraints (multiple design fields, frequencies, etc.)
  - Nonlinear programming
  - Gradient information
- Possible algorithms
  - Gradient descent (incl. quasi Newton methods)
  - SQP
  - Interior point
  - **CCSA (MMA)**
- Optimization tips and tricks
  - Epigraph formulation!
  - **We can learn tricks from machine learning community!**
    - Initial starting conditions (weight distributions)
    - Filter evolution (dropout, pooling, etc.)
    - Hardware acceleration (GPU support, TPU support, etc.)



Relevant Publications

- A. M. Hammond, A. Oskooi, S. G. Johnson, and S. E. Ralph, "**Photonic topology optimization with semiconductor-foundry design-rule constraints**," *Opt. Express*, vol. 29, no. 15, pp. 23 916–23 938, Jul. 2021.
- A. M. Hammond, A. Oskooi, M. Chen, Z. Lin, S. G. Johnson, and S. E. Ralph, "**High-performance hybrid time/frequency-domain topology optimization for large- scale photonics inverse design**," *Opt. Express*, vol. 30, no. 3, pp. 4467–4491, 2022.
- A. M. Hammond, J. B. Slaby, M. J. Probst, and S. E. Ralph, "**Multi-layer inverse design of vertical grating couplers for high-density, commercial foundry interconnects**," *Opt. Express*, 2022.
- A. M. Hammond, J. Slaby, M. Probst, and S. E. Ralph, "**Phase-injected topology optimization for scalable and interferometrically robust photonic integrated circuits**," [*invited, under review*].
- A. M. Hammond, A. Oskooi, M. Chen, S. G. Johnson, and S. E. Ralph, "**Hybrid level-set and density-based topology optimization for integrated photonic design**," *Opt. Express*, 2022 [*in progress*].
- A. M. Hammond, A. Oskooi, S. G. Johnson, and S. E. Ralph, "**Robust topology optimization of foundry-manufacturable photonic devices: An open-source fdtd toolbox**," in *Frontiers in Optics*, Optical Society of America, 2020, FTh1C–4.
- A. M. Hammond and S. E. Ralph, "**Fabrication tolerant interferometric subsystems for large-scale photonic integration**," in *Integrated Photonics Research, Silicon and Nanophotonics*, Optical Society of America, 2021, IM4A–3.
- A. M. Hammond and S. E. Ralph, "," in Advanced Photonics, Optical Society of America, 2021, IM4A.3. **Fabrication tolerant interferometric subsystems for large-scale photonic integration**
- A. M. Hammond, J. Slaby, G. Saha, and S. E. Ralph, "**Robust topology optimization for foundry-photonics inverse design: Examining compact and arbitrary power splitters**," in *2021 European Conference on Optical Communication (ECOC)*, IEEE, 2021, pp. 1–4.
- A. M. Hammond, C. A. Kaylor, J. Slaby, M. Probst, and S. E. Ralph, "**Photonic inverse design of compact Stokes-vector receivers on commercial foundry platforms**," in *2022 European Conference on Optical Communication (ECOC)*, IEEE, 2022, pp. 1–4.

Acknowledgements

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PhD Defense: August 3, 2022 10:00 AM EST
(if interested, email me for Zoom link!)

See tomorrow's talk for more examples!

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